PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC, **118**: 1545–1549, 2006 November

Cepheids in Multiple Systems: ADS 14859[1]

NANCY REMAGE EVANS
Smithsonian Astrophysical Observatory, MS-4, 60 Garden Street, Cambridge, MA 02138

OTTO FRANZ
Lowell Observatory, 1400 Mars Hill Road, Flagstaff, AZ 86001

DERCK MASSA
NASA Goddard Space Flight Center, SGT, Inc., Code 681.0, Greenbelt, MD 20771

BRIAN MASON[2]
Astrometry Department, US Naval Observatory, 3450 Massachusetts Avenue NW, Washington, DC 20392-5420;
and Center for High Angular Resolution Astronomy, Georgia State University, Atlanta, GA 30303

RICHARD L. WALKER
US Naval Observatory. Deceased

AND

MARGARITA KAROVSKA
Smithsonian Astrophysical Observatory, MS-70, 60 Garden Street, Cambridge, MA 02138

Received 2006 April 4; accepted 2006 September 29; published 2006 November 7

ABSTRACT. We have attempted to resolve the system containing the Cepheid V1334 Cyg (=ADS 14859) using both the Faint Object Camera (FOC) and the Fine Guidance Sensor (FGS) on the *Hubble Space Telescope*, and also using ground-based speckle interferometry with 4 m class instruments. None of these approaches was successful, leading to upper limits of approximately 20 mas (depending on the magnitude difference between the stars). We discuss constraints this places on a possible wide orbit as a guide to future observations.

1. INTRODUCTION

The quest for observed Cepheid masses has a number of motivations. Since Cepheids are primary extragalactic distance indicators, it is crucial to understand them quantitatively. The need for observed masses was underscored in the 1960s when hydrodynamic pulsation calculations predicted masses that differed from evolutionary tracks. This discrepancy has now been resolved through a reevaluation of envelope opacities. At present, Cepheid masses are one of the most important benchmarks for evolutionary tracks of intermediate-mass stars, because they can be coupled with a precise luminosity. In particular, they are very sensitive to the treatment of the boundary between the convective core and the radiative envelope in the main-sequence phase ("convective overshooting"), which is the main uncertainty in the calculations.

The value of masses motivates the study of multiple systems. HR 8157 (=HD 203156, ADS 14859, HO 286, V1334 Cyg, and WDS 21194+3814) has had a double-star designation for more than a century. Visual observers have repeatedly listed a separation of 0″.1–0″.2. The two stars were reported as having the same magnitude. The system has a combined magnitude of $V = 5.87$ and a color of $B - V = 0.50$.

There have also been a number of attempts to resolve the pair by interferometry, as discussed below. A tentative orbit was derived based on a carefully culled subset of visual observations (R. L. W.) and interferometric data (B. M.). Although a full orbit had not been observed, it appeared that it might produce mass information. When enough of the orbit has been observed to include a node (van Albada 1962), a^3/P^2 ($=M_A + M_B$, the "mass parameter") is well determined, where P is the period, a is the semimajor axis of the orbit, and $M_A + M_B$ are the primary and secondary masses, respectively. On the basis of this tentative orbit, we attempted to resolve the system using several instruments on the *Hubble Space Tele-*

[1] Based on observations made with the NASA/ESA *Hubble Space Telescope* at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. These observations are associated with programs GO-7478, GO-8440, and GO-8772.

[2] Visiting Astronomer, Kitt Peak National Observatory, National Optical Astronomy Observatories, operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the National Science Foundation.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
NOV 2006	**N/A**	**-**

4. TITLE AND SUBTITLE
Cepheids in Multiple Systems: ADS 14859

5a. CONTRACT NUMBER
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER
5e. TASK NUMBER
5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Library U.S. Naval Observatory 3450 Massachusetts Avenue, N.W. Washington, D.C. 20392-5420

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR’S ACRONYM(S)

11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**5**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

scope (*HST*). The observations and our results are the topic of this paper.

The system became a particularly interesting one when Millis (1969) discovered that the primary, an F3 II bright giant, has low-amplitude pulsation with a period of 3.3 days. This is an appropriate spectral type and period for a classical Cepheid. Evans (2000) concluded that it is pulsating in the first overtone, based on Fourier diagnostics of the light curve.

In addition, shortly after the pulsation was discovered, Abt & Levy (1970) discovered orbital motion in the Cepheid radial velocities. Evans (2000) derived an orbit with a period of 5.3 yr. This is much shorter than any orbit related to the 0\".1 separation reported by visual observers, and it implies an additional component in the system.

The hottest star in the system has been studied with *International Ultraviolet Explorer* (*IUE*) spectra (Evans 1995). From an *IUE* high-resolution spectrum of ADS 14859, Evans (2000) tentatively concluded that the hottest star in the system is the companion in the long-period orbit, because the velocity of the strong lines near 1300 Å is close to the systemic velocity of the Cepheid short-period orbit. By comparing the Cepheid and the hottest companion with isochrones, a mass of 4.4 $M_{\odot}$ was inferred for this companion. From the short-period orbit itself, it was concluded that the companion in this orbit is also fairly massive, more massive than 3.1 $M_{\odot}$.

This paper discusses attempts to resolve the wide companion and the Cepheid plus close companion pair using *HST*. The sections below describe the observations and discuss the speckle interferometry, magnitude difference, and information about the wide orbit.

2. OBSERVATIONS

2.1. FOC (Faint Object Camera) Observations

ADS 14859 was observed with the *HST* FOC in 1998 October (Table 1). The *HST* archive contains the full details of the observation.[3] The observation was heavily filtered so that only flux between 1600 and 2000 Å was present. FOC pixels are 0\".014 on a side, and FWHM of the FOC is 0\".03 at 2000 Å. Thus, based on the expected separation of the stars from the tentative orbit of 0\".08, we should have been able to resolve the two stars easily, particularly in the ultraviolet, where the brightness of the Cepheid primary and the hot secondary are more equal than in the visible.

In order to search for the companion in ADS 14859, the observations were compared with an appropriate FOC image of an unresolved point source. No additional source was detected at the expected position of the companion. We searched for a source closer to the primary star, using the Richardson-Lucy technique (Richardson 1972; Lucy 1974) to deconvolve the observation with the observed point-spread function (PSF). The result did not show credible extra sources above the noise level, or a source that could be separated from the artifacts in the PSF (FOC PSF images showing the artifacts surrounding the central core can be viewed online).[4]

[3] See http://archive.stsci.edu.

TABLE 1
HST Observations of ADS 14859

Instrument	Date
FOC ……	1998.81
FGS ……	1997.60
FGS ……	1999.58
FGS ……	2000.59

2.2. FGS (Fine Guidance Sensor) Observations

A series of observations were made with the *HST* FGS in a further attempt to resolve the system (Table 1). These observations were planned and reduced by one of us (O. F.), based on considerable experience with the FGS. The first observation was obtained with Fine Guidance Sensor 3 (FGS3) on 1997.60. The data reduction and analysis, although much more exhaustive than had usually been necessary in the case of any resolvable binary system, produced no evidence whatsoever for nonsingularity of this target. If the stars had the expected angular separation of approximately 20 mas, they should have been resolvable.

One possible interpretation of this finding is that an unexpectedly peculiar orbital geometry may have caused the angular separation of the "wide" component of the system to be much smaller than predicted for the epoch of observation from analyses of ground-based positional observations. Numerical experiments synthesizing binary-star TRANS (transfer function scan mode) functions with the use of single-star scans indeed showed convincingly that a companion at a separation of 20 mas and a magnitude difference ≤2 mag would have been detectable by FGS3 TRANS observations. On the other hand, a companion at a smaller separation could have escaped detection, owing to the degraded performance of FGS3 in TRANS mode.

Following the installation of FGS1r and its commissioning as the *HST* astrometer, two observations of ADS 14859 were obtained: one on 1999.58, the second on 2000.59. Our preliminary analyses of both observations looked encouraging. However, a definitive analysis of these observations could not be made until calibration data for a single star of appropriate $B-V$ color, observed with same filter (F5ND), were taken under the FGS1 TRANS calibration program.

The first and only F5ND observation of a "single" star of a color (HD 37501, $B-V=0.85$) suitable to represent the Cepheid TRANS scans was not obtained until 2001.81. An observation of a blue star (HD 38666, $B-V=-0.28$) that

[4] See, e.g., Fig. 27 of the FOC Handbook, ver. 7.0, http://www.stsci.edu/ftp/instrument_news/FOC/foc_handbook.html.

would have been useful to represent the contribution of the elusive "wide" companion had failed on 2001.79 and was not rescheduled and successfully executed until 2002.13. Aside from the obvious consequence of greatly delaying the data analysis, these long lags between science and calibration observations also give rise to the possibility that owing to intervening changes in the TRANS function morphology, the calibrations may no longer be fully relevant to the science data. Such changes have long been documented but never satisfactorily interpreted. Occasional refocusing of the telescope may be responsible. With only isolated calibration observations available, we cannot detect, let alone cope with, the effects of such possible changes. Owing to these calibration issues, the angular resolution limit with FGS1r is probably not better than 0″.020, the actual value depending on effective magnitude differences and scan geometries.

When we were finally able to resume the analysis of the FGS1r observations as best and as completely as the available tools permitted us to do, our initial hopes for detection and measurement of the "wide" companion were thoroughly frustrated. Attempts at direct analysis, extensive parameter searches including higher order multiplicity, and efforts to model the observations with various reasonable combinations of angular separations and intensity ratios gave, in some instances, either formal "solutions" or at least indications of duplicity. However, comparison of such tentative "results" for the two FGS1r observations, and attempts to reconcile them with each other and with a coherent dynamical characterization of the system, always led us to conclude that our "results" were spurious. They were certainly inconsistent with the record of ground-based "observations," historic and recent, and were incompatible with any orbital analyses based on this record.

3. DISCUSSION

3.1. Speckle Interferometry

Published interferometric observations of ADS 14859 are, for the most part, a series of nondetections. The historical data[5] cover the time from 1976 to 1993 and are summarized in Table 2. Archive rereduction of data obtained by the Center for High Angular Resolution Astronomy (CHARA), as well as two new nondetections obtained in 2001 and 2005 (see below), are included as well. The first three columns of Table 2 give the date of observation (as a fraction of the Besselian year), position angle θ (in degrees), and separation ρ (in arcseconds). Column (4) gives the effective wavelength and FWHM of the filter used, in nanometers, while column (5) gives the aperture of the telescope. The references are listed in column (6), and the observation notes are given at the bottom of the table.

There were three resolutions of the system from 1968.6568

TABLE 2
SPECKLE INTERFEROMETRY MEASUREMENTS OF ADS 14859

Date (1)	θ (deg) (2)	ρ (arcsec) (3)	$\lambda_0/\Delta\lambda$ (nm) (4)	Telescope Aperture (m) (5)	Reference (6)
1976.8594	...	<0.035	552/20	3.8	1
1977.487	...	<0.035	552/20	3.8	2
1978.618	...	<0.030	470/...	3.8	2
1979.5296	...	<0.033	470/...	3.8	3
1979.7727	...	<0.033	470/...	3.8	3
1980.477	...	<0.030	470/...	3.8	2
1980.720	...	<0.030	470/...	3.8	2
1981.703	...	<0.030	470/...	3.8	2
1982.7600	...	<0.023	350/20	3.8	4
1983.4314	...	<0.036	549/22	3.8	4
1983.4341	...	<0.036	549/22	3.8	4
1983.7100	...	<0.036	549/22	3.84	4
1984.7040[a]	...	<0.036	549/22	3.8	4
1986.6568	166.4	0.035	...	6.0	5
1988.5039	165.8	0.052	549/22	3.8	4
1988.6568	165.0	0.054	550/...	1.0	6
1990.4437	170.1	0.073	550/...	1.0	6
2001.5019	...	<0.030	550/24	3.8	7
2005.8681	...	<0.030	550/24	3.8	7

REFERENCES.—(1) McAlister 1978; (2) Hartkopf & McAlister 1984; (3) McAlister & Hendry 1981; (4) CHARA archive rereduction; (5) Balega et al. 1989; (6) Ismailov 1992; (7) this paper.

[a] This observation is elongated in a north-south direction, possibly indicating a component just under the resolution limit.

to 1990.4437, which can be found in Balega et al. (1989) and Ismailov (1992). It should be pointed out that the Ismailov measurements of 54 and 73 mas were made with a 1.0 m telescope. A telescope of this size operating at 550 nm has a Rayleigh limit of 138 mas, so these two measurements should be regarded as suspect.

Six CHARA observations from 1982.76 to 1988.67 were reanalyzed using the techniques described in Bagnuolo et al. (1992). As discussed in Mason (1996), these new reduction algorithms, which increase the signal-to-noise ratio by a factor of about 3, allow for the detection of fainter peaks or the measurement of peaks that were previously too weak to measure in about one out of eight cases. In this case, they were successful once and partially successful once. The one measurement was made at about the same time as the Balega et al. (1989) measurement and is consistent with it. The strength of the peaks is weak, however, and were it not for the measurement by Balega et al., this might have been regarded as too weak to measure. The strength of the peaks is consistent with a large Δm.

Twice recently (2001.5019 and 2005.9691) we attempted recovery of the secondary, using the Kitt Peak National Observatory 4 m reflector with the US Naval Observatory speckle camera. This system is virtually identical to the CHARA speckle camera, but with a more sensitive detector (Mason et al. 1999). While the data from these two observations have not been finalized for publication, it is certain that the secondary

[5] See the Fourth Catalog of Interferometric Measurements of Binary Stars, http://ad.usno.navy.mil/wds/int4.html, for the details on these observations.

was not recovered on these two occasions. In Table 2, they are designated <0$''$.030.

The weight of the evidence in Tables 1 and 2 is that the system has not been resolved in the period since 1976, despite an improvement in equipment and techniques

3.2. Magnitude Difference

One feature that can confound resolution attempts using interferometric techniques is a large magnitude difference between component stars. Visual observers have typically found the two stars to be very similar. Aitken (1932) describes the quadrant as "always indeterminate." Jeffers et al. (1963) give a magnitude difference of zero, and while the magnitude of the stars as listed in the Washington Double Star database[6] varies, the differential magnitude does not. It is consistently zero.

On the other hand, the energy distribution of the star from 1200 to 3200 Å is available from an *IUE* spectrum (Evans 1995). A magnitude difference of 2.2 mag is found from comparisons with a standard-star spectrum. This applies, of course, to the Cepheid and the hottest star in the system. This star has tentatively been identified with the wide companion in the system from a velocity measurement on an *IUE* high-resolution spectrum (Evans 2000). The bolometric magnitude difference is of course smaller, and this might be reflected in the visual estimates of the magnitude difference.

The detection of double stars by speckle interferometry is strongly influenced by both seeing conditions and magnitude difference. The problem was discussed in Mason et al. (1993), where artificial binaries were created by inserting a calcite crystal in the optical path and rotating the crystal to generate magnitude differences, assuming the (Malus) $\tan^2$ law. In this case, for a star with a brightness similar to ADS 14859, the secondary can be detected, given a Δm less than 3.5.

Further evidence comes from the investigation of binaries with known Δm values (Mason 1995a, 1995b). HR 1411 (=HD 28307, McA 15) has a mean Δm, as determined by 17 lunar occultation measurements, of 3.62 ± 0.39. An additional system that is not as bright but has a large Δm is BD +20 2150 (=HD 73574, CHARA 156 Da). This system has a mean Δm in the blue (red) of 3.05 (3.78). Both of these systems are routinely detected by the CHARA speckle program from many different telescopes, with seeing conditions ranging from excellent to poor.

Given these two systems and the simulation results above, a conservative estimate of the Δm limit of the CHARA speckle system is 3.0.

3.3. Orbit?

We have expended considerable effort in trying to apply appropriate weights to the available data and determine a reasonable orbit, starting with the first tentative orbit (R. L. W.). Unfortunately, we have met with no success here.

What can we say about this system at this point? We summarize below the known facts about this system.

1. The visual observers have repeatedly reported that ADS 14859 is elongated and is made up of two stars of approximately equal brightness. If this is the case, the fact that the system has not been resolved in the last two decades, with many attempts at interferometry with a typical limit of 0$''$.03, implies that the system has a long period of 100 yr or more. We recommend occasional attempts to resolve the system in the future. If it is resolved, an orbit should produce valuable mass information, as we had hoped to do.
2. The orbital period of the close orbit (Evans 2000) is 5 yr. Tokovinin (2004) found that in stable multiple systems, this means the period of the long-period system is greater than 25 yr. This is comfortably within the estimate in item 1. As discussed in Evans et al. (2005), triple systems are very common in Cepheids with known orbits.
3. In our working model, the Cepheid is in a short-period (5 yr) orbit, with a more distant companion in a much wider orbit that we were unable to resolve. The hottest star in the system was tentatively identified with the wide companion, but in this case (Evans 2000) the companion in the short-period orbit is also quite massive. We note that in the future, resolving the system in the far-ultraviolet (1200–2000 Å) would be particularly important, since this would provide information about the spectral type and mass of the third star.

In summary, we provide an upper limit on the separation of the stars in the wide binary containing ADS 14859, of approximately 0$''$.02 (depending somewhat on the brightness of the stars). This, plus the short-period orbit, provides constraints on the system and its components. It would be of great value to resolve the system in the future.

This project was begun many years ago by conversations with Dr. J. D. Fernie, and in the tentative orbit derived by Dr. R. L. Walker. We regret the passing of our colleague, Richard L. "Dick" Walker. He was a studious and very careful observer of doubles, and over the years made over 8000 measurements of doubles, resulting in almost 3000 mean positions. While contributing to the measurements of known systems for orbital analysis, he discovered 22 pairs, mostly additional components to known systems. Dick also ventured into other areas of astronomy, among them discovering Epimetheus, a moon of Saturn, in 1966 December with the USNO Flagstaff Station's 61$''$ astrometric reflector. We are sorry to lose a colleague so knowledgeable about the long string of observations that make the study of systems such ADS 14859 possible.

We are happy to acknowledge financial support from STScI grant GO-07478.01-96A and also *Chandra* X-Ray Center NASA contract NAS8-03060 (for N. R. E. and M. K.).

[6] See http://ad.usno.navy.mil/wds/wds.html.

REFERENCES

Abt, H. A., & Levy, S. G. 1970, PASP, 82, 334

Aitken, R. G. 1932, New General Catalogue of Double Stars within 121° of the North Pole (Washington: Carnegie Inst.)

Bagnuolo, W. G., Jr., Mason, B. D., Barry, D. J., Hartkopf, W. I., & McAlister, H. A. 1992, AJ, 103, 1399

Balega, I. I., Balega, Y. Y., & Vasyuk, V. A. 1989, Astrofiz. Issled. Izv. Spets. Astrofiz. Obs., 28, 107

Evans, N. R. 1995, ApJ, 445, 393

———. 2000, AJ, 119, 3050

Evans, N. R., Carpenter, K. C., Robinson, R., Kienzle, F., & Dekas, A. 2005, AJ, 130, 789

Hartkopf, W. I., & McAlister, H. A. 1984, PASP, 96, 105

Ismailov, R. M. 1992, A&AS, 96, 375

Jeffers, H. M., van Denbos, W. H., & Greeby, F. M. 1963, Index Catalogue of Visual Double Stars, 1961.0 (Publ. Lick Obs. 21; Mt. Hamilton: Lick Obs.)

Lucy, L. B. 1974, AJ, 79, 745

Mason, B. D. 1995a, Catalog of Photoelectric Measures of Occultation Binary Stars, CHARA Contrib. No. 3, (Atlanta: Georgia State Univ.)

———. 1995b, PASP, 107, 299

———. 1996, AJ, 112, 2260

Mason, B. D., McAlister, H. A., Hartkopf, W. I., & Bagnuolo, W. G. 1993, AJ, 105, 220

Mason, B. D., et al. 1999, AJ, 117, 1890

McAlister, H. A. 1978, ApJ, 223, 526

McAlister, H. A., & Hendry, E. M. 1981, PASP, 93, 221

Millis, R. L. 1969, Lowell Obs. Bull, 7, 113

Richardson, W. H. 1972, J. Opt. Soc. Am., 62, 55

Tokovinin, A. 2004, in Rev. Mexicana Astron. Astrofis. Ser. Conf. 21, The Environment and Evolution of Double and Multiple Stars, ed. C. Allen & C. Scarfe (Mexico: UNAM), 7

van Albada, G. B. 1962, Bull. Astron. Inst. Netherlands, 16, 178